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A digital television error-protection scheme based on waveform estimates

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A DIGITAL TELEVISION ERROR-PROTECTION SCHEME BASED ON WAVEFORM ESTIMATES

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Summary

An error-protection scheme is described which is applicable where the television signal is sampled at three-times colour subcarrier frequency. In this scheme, the otherwise redundant frequency band between 5·5 MHz and half-sampling frequency (6·65 MHz) is used for measurements to identify whether any digit errors have been introduced into the digital signal and the magnitude of such errors. Thus, the signal is protected against the effects of such errors without the use of parity check digits.

Apparatus was constructed to test the feasibility of this error-protection scheme. Results were encouraging in that the system was more efficient when the errors had greatest effect on the waveform; errors in the most significant bit being put right more than 99·9% of the time.

Limitations were discovered with the particular instrumentation of this scheme such that it was only effective for errors in the three most significant digits. It is estimated that the performance of such a system could be improved at the cost of increasing the complexity of the apparatus. However, the apparatus used would probably then be more complex than for more common forms of error protection which use parity digits added to the digital signal prior to transmission for checking the data at a receiving terminal.

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1. Introduction

A range of error-protection systems for digital television have been proposed[1] where the use of parity check digits is replaced either partly or wholly by making use of redundancy in the television signal. One form of this redundancy arises when a System I television signal, where bandwidth is limited to 5·5 MHz, is transmitted in digital form with a sample-rate of three-times colour subcarrier frequency ($3f_{sc}$). Here, the digital system can convey signals at frequencies up to half the sampling rate (6·65 MHz) and the band between 5·5 MHz and 6·65 MHz is redundant; this band normally only containing residual signal components which are passed by practical low-pass filters designed to pass, unattenuated, signal components up to 5·5 MHz.

To exploit this form of redundancy, it was proposed that waveform estimates could be formed for each received sample value, on the basis that no signal energy would be expected at frequencies above 5·5 MHz. These estimates would be used to locate any erroneous samples which would then be replaced by the estimated values.

This report describes an error-protection scheme, based on the principles outlined above, and tests made to assess the feasibility of such a scheme for application to a $3f_{sc}$ sampled digital video signal.

2. The error-protection scheme

2.1. General

A schematic of the error-protection system, based on redundancy at high frequencies in a $3f_{sc}$ sampled signal, is shown in Fig. 1. An estimating filter can be designed where estimates of each sample value are formed from surrounding samples on the basis that no signal frequencies are present above a cut-off frequency. However, as described in Reference 1, it is more convenient in locating the position of an error to subtract the estimate from each received sample value. Thus, the measurement filter used in the error-protection system shown in Fig. 1 becomes a high-

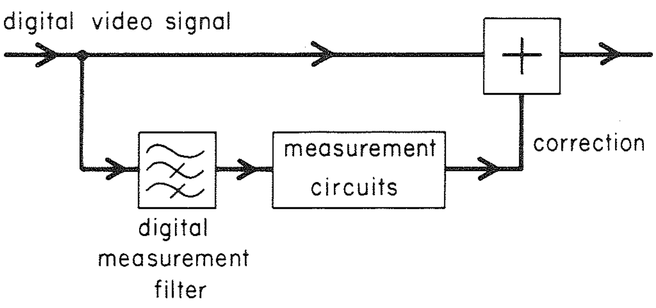


Fig. 1 - Block schematic showing the error-protection system

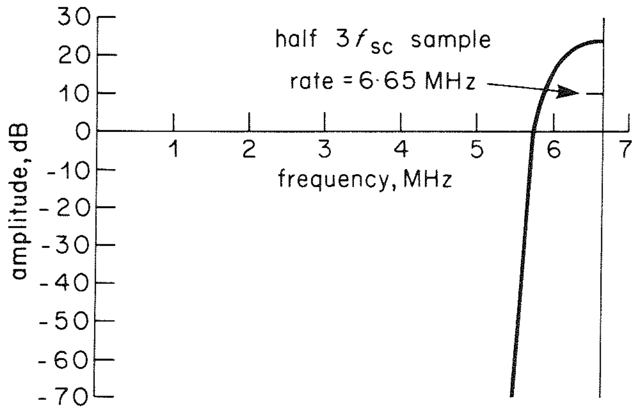


Fig. 2 - Amplitude/frequency characteristic of an ideal measurement filter

pass filter (with an upper limit at half the sampling frequency). The output from the filter is normally zero except when an erroneous digital sample is received. Then, the output is the impulse response of the measurement filter and has a magnitude proportional to the difference between the erroneous sample value and the original sample value.

The amplitude/frequency characteristic and the impulse response of a digital transversal filter, ideal for use as a measurement filter, are given in Figs. 2 and 3. These are normalised such that if a sample of value S, preceded and followed by samples of zero value, is applied to the filter input, the output from the filter, which occurs at the centre of the impulse response, is equal to S. The frequency response of this filter is zero in the video pass-band and rises to a larger than unity gain at half sampling fre-

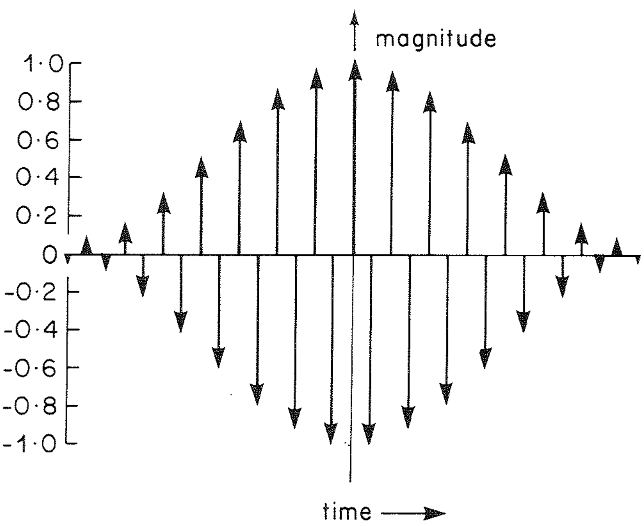


Fig. 3 - Impulse response of an ideal measurement filter

quency. The impulse response is symmetrical in time and has a minimum total length, consistent with the frequency response, such that there is the highest probability of resolving errors in sample words which are close together.

Apart from the measurement filter, the error-protection apparatus, shown in Fig. 1, comprises measurement circuitry in which measurements are made of the signal at the output from the filter. Based on these measurements, samples are deemed erroneous and the magnitudes of corrections to be applied to those samples are ascertained. In practice, these measurements must be made in the presence of television signal components and noise which have been passed by the measurement filter. In the presence of such interference, erroneous samples will hopefully still be corrected and the error-protection scheme will not be triggered overmuch by the spurious signals.

2.2. The measurement filter

A digital transversal filter was available for the practical implementation of this error-protection scheme which, although of somewhat limited performance, was thought adequate for the present study. The main limitations of this filter were that only sufficient sections were available to synthesize filters whose impulse responses were symmetrical and obtained by multiplying the signal by up to 23 coefficients, one central term and eleven either side. Also, each coefficient was quantised in steps of 1/64 over the range +1 to −1 (128 steps in all). The limited number of sections and the coarse quantisation of the coefficients both limited the range of filter characteristics which could be generated. However, within the filter 12 binary digits were provided for the signal during processing.

In specifying the filter characteristic to be used, it was found convenient to have a pair of coefficients, one either side of the central term, both equal to +½ or −½. This simplified the design of measurement circuits which will be discussed in the next Section (2.3).

Within the constraints set out above, it was found that the filter characteristics that could be generated did not approach the ideal very closely. Three examples of com-

TABLE 1

Coefficients for the filters

	Coefficients											
	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
First filter	+64	−62	+55	−44	+32	−21	+12	−5	+1	0	−1	+1
Second filter	+64	−62	+57	−50	+41	−32	+23	−16	+10	−5	+3	−1
Third filter	+64	−62	+57	−50	+41	−32	+23	−15	+9	−5	+3	−1

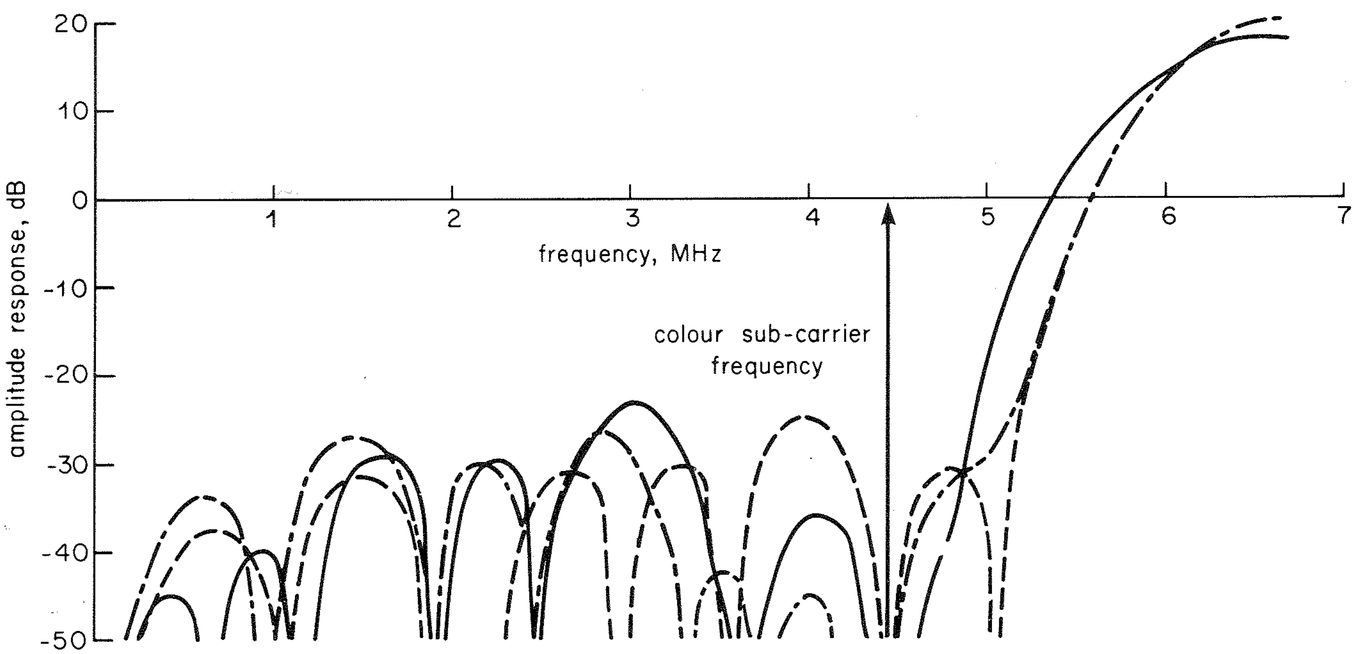


Fig. 4 - Computed amplitude/frequency characteristics of three filters obtained by different settings of the practical measurement filter

Filter 1 ——— Filter 2 —·— Filter 3 – – –

puted characteristics are given in Fig. 4. The coefficients for these filters are shown in Table 1 where C_0 is the central term and C_1 to C_{11} are coefficients on one side of that central term. To avoid fractions, the coefficients are shown as number of quantum steps and are 64 times their numerical values.

All three examples of characteristics of the practical filter given in Fig. 4 have a wider pass-band than that of the ideal response given in Fig. 2. This is a direct result of the practical filter not having as many sections as the ideal. Also, as a direct result of the quantisation of the coefficients of the filter, the responses are not insignificant within the video pass-band. The effect quantisation has on the response of the filter is illustrated by the difference between the responses of filter examples 2 and 3 in Fig. 4 which is caused by adjusting two of the coefficients each by one quantum step.

Attempts to optimise the settings of the filter coefficients showed the examples given to be as good as could be achieved within the constraints. Tests with the error-protection scheme, which will be described later in Section 4.3, were made to assess the suitability of each of these characteristics.

2.3. Measurement method

As discussed in Section 2.1, the measurement circuits identify any samples which are in error and the magnitudes of the errors. To do this, measurements are made on the signal at the output of the measurement filter which, as well as impulse waveforms which are the result of errors, includes spurious signals such as television signal components not sufficiently attenuated by practical measurement filters like those described in Section 2.2 above.

The measurement scheme adopted to locate any samples in error, is derived from one in which attempts are made to match the output waveform from the measurement filter (ignoring an amplitude scaling-factor) with the known impulse response of the measurement filter. With such a system, an error would be assumed to have occurred at every sample instant, equal in magnitude to the output from the measurement filter at that instant. Checks would then be made on sample values at the output from the filter before and after that instant, to see if they match the filter impulse response for that error. Repeating the process at each sample instant, the samples could be deemed erroneous where, in a sequence of checks, the impulse response for the assumed error best matches the output from the measurement filter.

In the practical measurement system, the error impulse waveforms at the output of the measurement filter were only checked at two instants, one each side of the central term, where the amplitudes would be half that of the central peak. At these instants the slope of the envelope of the impulse waveform is greatest, such that the difference between results obtained at sample instants adjacent to an error is greatest. Further, to generate these values for test purposes only requires the value of the central point to be halved.

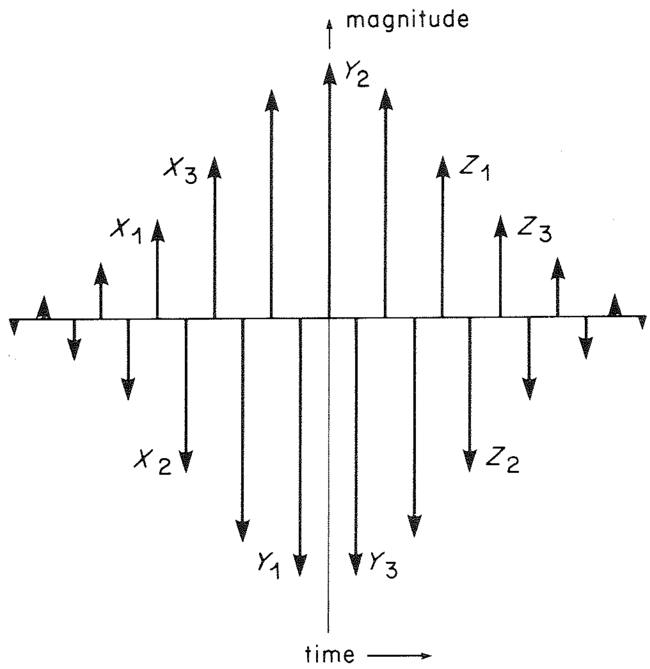


Fig. 5 - Identifying which of Y_1, Y_2, Y_3 is in error from the output of the measurement filter when an error is present in the digital television signal

The process used in identifying samples which are in error is illustrated in Fig. 5 which shows the impulse response of the measurement filter which is similar to the output expected from the filter when an error is present. In three successive attempts to find whether Y_1, Y_2 or Y_3 is the sample in error, Y_1 is tested by comparing $\frac{1}{2}Y_1$ with X_1 and Z_1, Y_2 by comparing $\frac{1}{2}Y_2$ with X_2 and Z_2 and Y_3 by comparing $\frac{1}{2}Y_3$ with X_3 and Z_3. A generalised expression, which summarises the method is: Difference $D = |X_n - \frac{1}{2}Y_n| + |Z_n - \frac{1}{2}Y_n|$ or in the case where X_n and Z_n are of opposite sign to Y_n, $D = |X_n + \frac{1}{2}Y_n| + |Z_n + \frac{1}{2}Y_n|$. An error is deemed present where the value of D is a minimum.

Fig. 6 shows the difference signal D, decoded and displayed on an oscilloscope, when an error waveform, similar to that shown in Fig. 5, is applied. In this case the D_{min} is clearly defined. To reject minima in D which might be caused by spurious signals, the correction process is inhibited unless the value of D at D_{min} is less than a threshold $T_{D\,min}$. The correction process is also inhibited unless the value of the correction being applied exceeds a threshold T_{corr}. These thresholds were made adjustable and were set, during tests, to give best performance of the error-protection system.

3. The test apparatus

The arrangement of apparatus used in tests to assess the performance of the error-protection system is shown in Fig. 7. Test pictures were provided by means of a slide scanner; this was the picture source which gave the best definition and greatest high-frequency content of pictures.

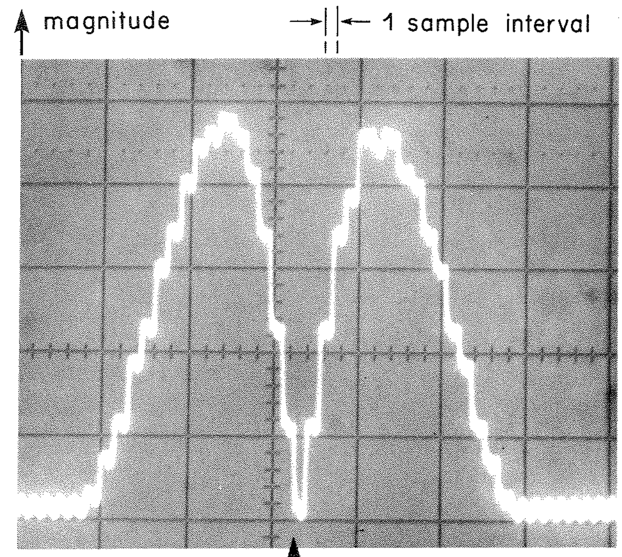


Fig. 6 - Difference signal D for an error in the third significant digit

From a wide range of colour slides, three particularly critical slides were selected and used for the tests. Monochrome versions of the pictures are reproduced in Fig. 8.

Prior to p.c.m. coding, the television signal was applied to a low-pass filter commonly used for television signals sampled at $3f_{sc}$; its amplitude/frequency characteristic is shown in Fig. 9.

At the output of the analogue-to-digital converter, errors were generated in the digital signal at a regular rate by inverting digits of a particular significance. Facilities were also provided to enable errors to be generated in two sample words close together.

Monitoring facilities were provided to enable the action of the error-protection system to be monitored. The difference signal D, together with logic control pulses from the measurement circuit, were applied to a digital re-circulating store and thence via a digital-to-analogue converter to an oscilloscope. Thus the individual actions of parts of the measurement circuit were studied to trace the causes for any failures or spurious actions of the error-protection system.

Means were provided for replacing a video sample which would have been corrected with a code equivalent to peak-white video. This facility enabled instances where the error-correction process was triggered by signal components to be readily identified when the final corrected video signal was decoded and displayed on a television monitor.

4. Adjustment of the error-protection system

4.1. Initial observations

First tests with the error-protection system showed it particularly efficient in correcting errors in the first and second most significant digits. With errors in the third significant digit, the error-protection system failed occasionally although the overall effect was still a considerable reduction in the impairment of the signal caused by the errors. For errors in the fourth significant digit, and in digits of lower significance, the error-protection system did not give any worthwhile reduction in the signal impairment. Therefore, it was decided to select thresholds and a setting of the measurement filter to optimise the performance for errors in the three most significant digits.

4.2. Adjustment of thresholds for the measurement circuits

As discussed in Section 2.3, the measurement circuits incorporate two adjustable thresholds. If a minimum of D exceeds $T_{D\,min}$, or if the correction to be applied is less than T_{corr}, then confidence in the location of an error is not high. Moreover, if small corrections were permitted, they would frequently be triggered by television signal information passed by the measurement filter.

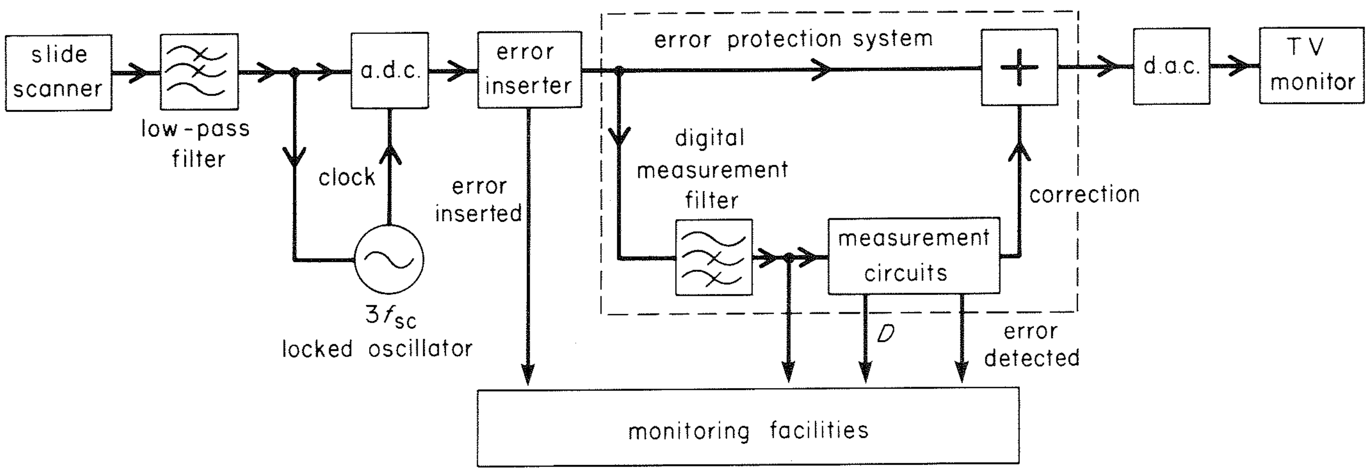
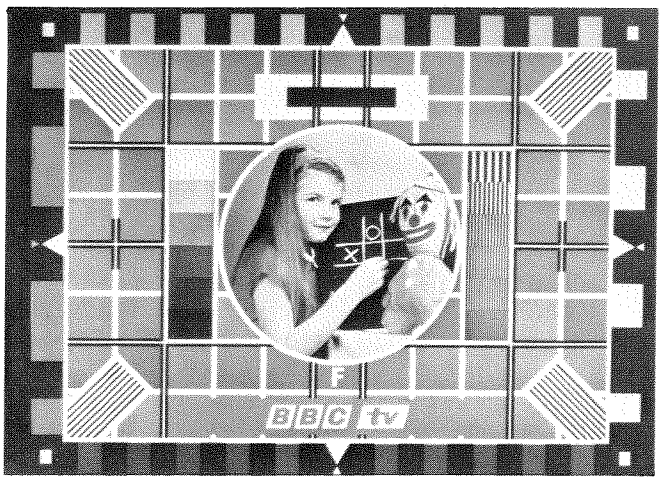
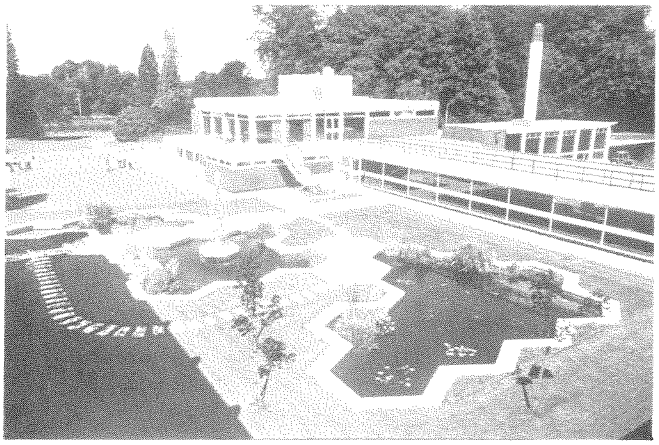


Fig. 7 - Block schematic showing arrangement of test apparatus



(a)

(b)



(c)

Fig. 8 - Monochrome prints of colour slides found particularly critical for the protection system
(*a*) Test Card F (*b*) Boy with toys (*c*) Formal pond

The optimum setting for $T_{D\,min}$ was found to be 1/16 of the peak of the D signal when there was an error present in the most significant digit. This was a compromise setting such that the performance on errors in the most significant digit was not impaired and the error-protection system was not triggered overmuch in samples surrounding errors.

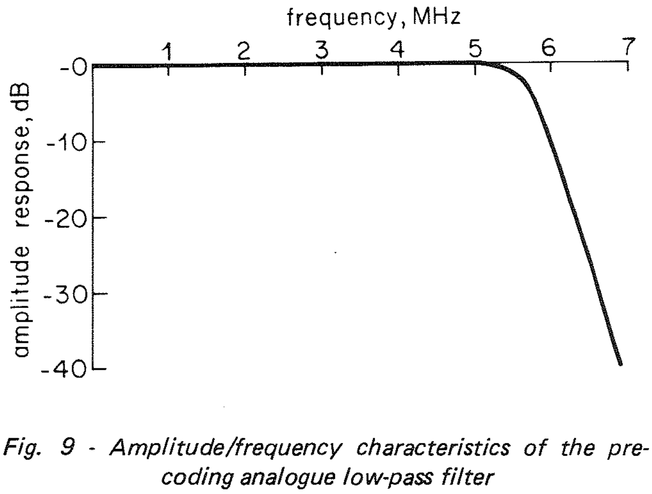


Fig. 9 - Amplitude/frequency characteristics of the pre-coding analogue low-pass filter

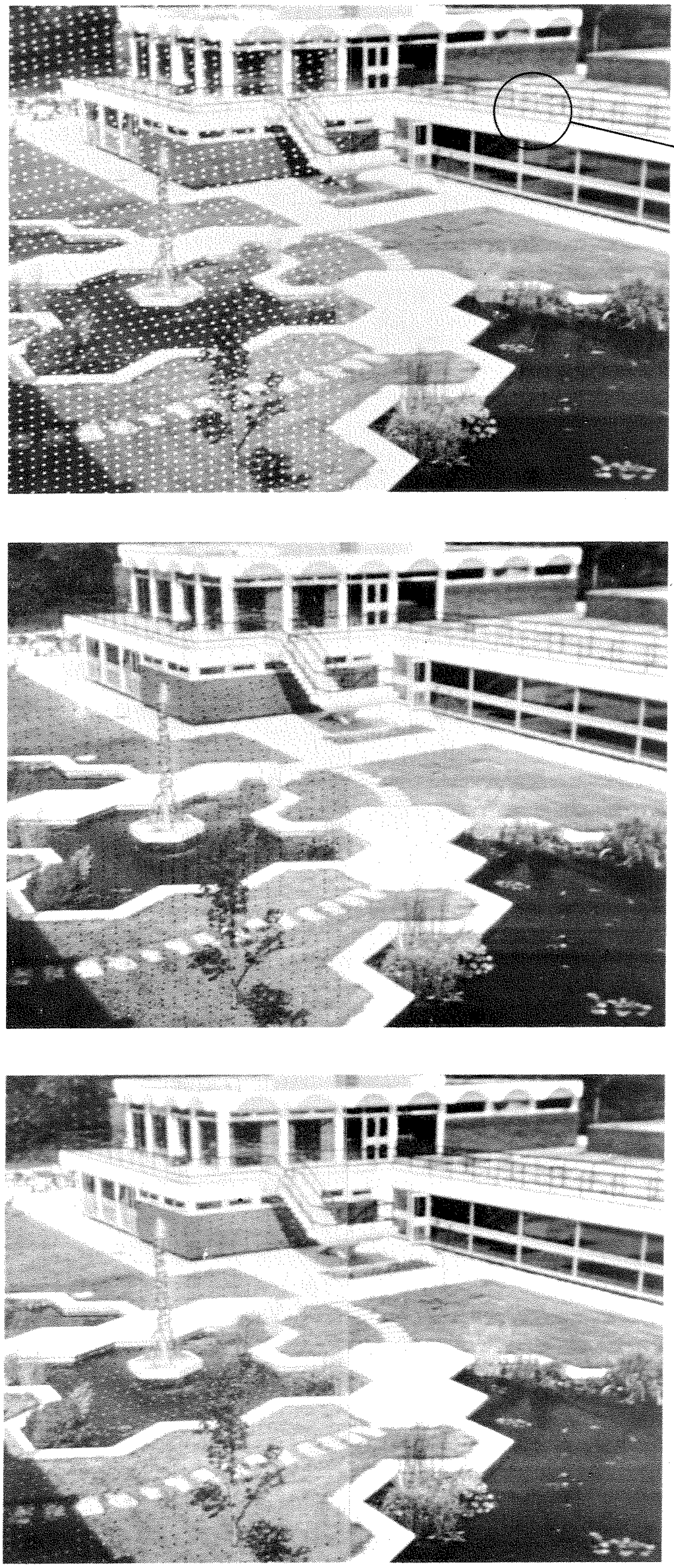
The optimum setting for the threshold T_{corr} was such that errors in digits less significant than the fifth were not corrected.

4.3. Tests with different settings of the measurement filter

The effect of changing the characteristics of the measurement filter was to vary the effectiveness of the error-protection system in different areas of the test pictures. To identify which effects were associated with different frequency components, tests were made using an electronically generated sine-wave signal, whose frequency increased line by line throughout each television field.

Thus, failures of the error-protection system to correct errors in the two most significant digits were found to occur when very high frequency signal information was present. Failures of the system to correct errors in the third significant digit occurred both at very high frequencies and at some lower frequencies. Some of the failures at lower frequencies could be attributed to the not insignificant response of the measurement filter at these frequencies (see Fig. 4), there being more failures at frequencies corresponding to peaks in the amplitude/frequency charac-

signal unprotected signal protected



seven failures of the error protection system to correct errors in this area

(*a*) Errors in most significant digit

(*b*) Errors in second digit

(*c*) Errors in third digit

Fig. 10 - Performance of error protection system

teristic than at other frequencies. However, there was also a background of failures of the system to correct some errors in the third significant digit at all frequencies. Failure to correct errors in the fourth significant digit seemed to occur independently of frequency.

Comparing the performance of the error-protection system with different measurement filter responses, filter No. 3 (Table 1) gave marginally better performance. Of the three, this filter had the narrowest pass band and gave fewest failures with errors in the two most significant digits.

5. Performance of the error-protection system

Tests were made to quantify the performance of the error-protection system using measurement filter No. 3 (Table 1) and the two thresholds, $T_{D\min}$ and T_{corr}, set as described in Section 4.2 above.

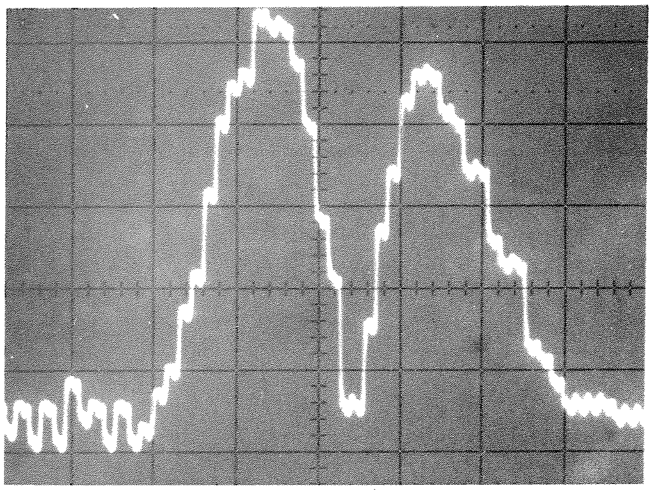
Of the test slides selected, the 'Formal Pond' (see Fig. 8) was found the most critical. The performance of the error-protection system with this test slide is illustrated in Fig. 10. For these photographs, errors were introduced in each of the three most significant digits of one sample in every 58; each complete picture containing about 7,000 samples in error. The photographs were each exposed for one television picture and the split screen effect obtained by joining together halves of photographs.

For errors in the most significant digit, close examination of the photograph showed the system failed to correct errors in seven samples. These failures occurred in the area outlined, where the original slide contains closely spaced railings which give rise to some very high frequency components.

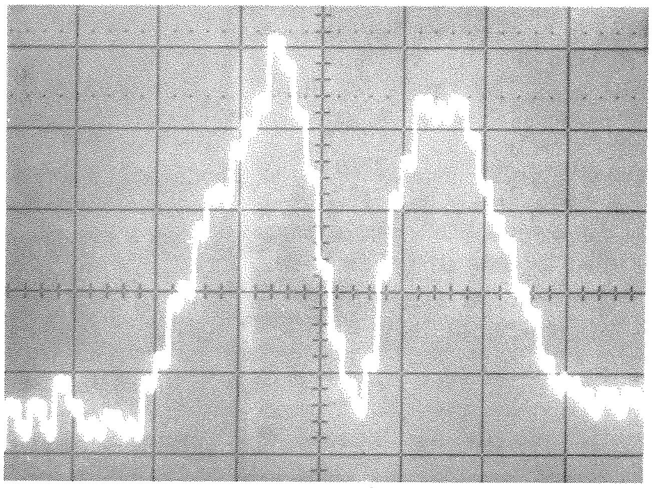
For errors in the second most significant digit, there were about twice as many failures of the error-protection system than with errors introduced in the most significant digit. Most of these failures are visible in the same area as before, but other failures also occurred in areas of the picture where sharp transitions generated high frequency signal components.

For errors in the third significant digit, there was a far greater number of failures. Most of these were also associated with high frequency signal components. In the illustration a large number have been masked by the photographic processes.

To provide a better measure of the efficiency of the error-protection system, the error-correction process was monitored, as described in Section 3. These observations showed that errors in the most significant digit were reduced by a factor of 10^3. For errors in the second bit the factor was 500, for the third bit 50 and the fourth bit 2. In the course of this work the actions of the various parts of the measurement circuits were observed. As a result, most failures of the error-protection system were traced to cases where the measurement circuits were not able to locate correctly which sample was in error. Two typical con-



(*a*) →| |← 1 sample interval



(*b*) →| |← 1 sample interval

Fig. 11 - D waveform for two typical failures to correct errors in the third significant digit

(*a*) Two successive samples both marking a minimum

(*b*) $D_{\min}$ delayed by one sample position

ditions arising with errors introduced into the third significant digit are illustrated in Fig. 11. These photographs show the decoded D signal from the measurement circuits. In the first photograph, Fig. 11(*a*), there are two consecutive values of D which are equal, giving an obvious ambiguity in error location. In this condition no correction is applied. In the second photograph, Fig. 11(*b*), the minimum has misleadingly moved to the adjacent sample position. In this case, the correction adds a further error, in the next sample, of equal sign and magnitude to the original error. Thus the error, which previously lasted for one sample, is now extended to two sample positions.

For errors in the fourth most significant digit, the minima of D are less clearly defined than with errors in the third digit. In a typical sequence, as well as the minima being lost or shifted there are also, in some cases, two or more minima of D close to the position of the error. In these cases more than one correction is made in the samples surrounding an error. Examination of the output of the

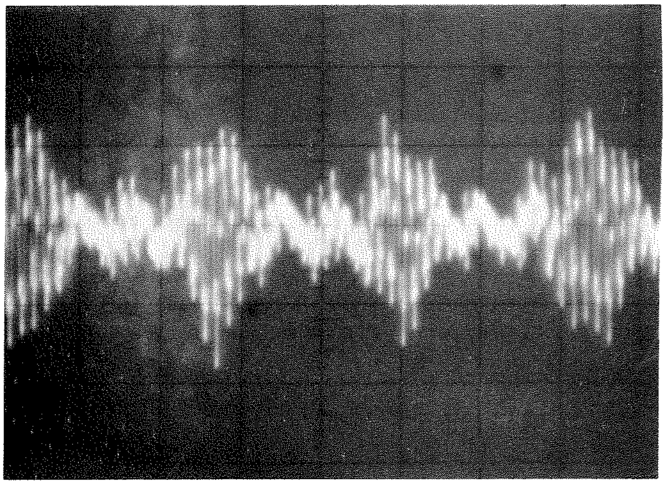


Fig. 12 - Output of the measurement filter with errors introduced into the fourth significant digit and a high level of spurious signal components passed by the filter

measurement filter for errors in the fourth significant digit shows that, in some cases, it would be very difficult for any measurement circuit to establish beyond doubt which sample is in error. In the case shown in Fig. 12, a combination of low frequencies and high frequencies passed by the measurement filter make location of an error in the fourth bit impossible. However, if the sample in error were known, a fairly accurate measure of the correction to be applied is available at the output of the measurement filter.

Some limited investigation of the effects of errors in pairs of samples close together was carried out. In general, it was found that the action of the error-protection system was not impaired when the distance between the erroneous samples was fifteen sample intervals or more. When the distance between errors was less than twelve, the action of the error-protection system was unpredictable, particularly when the errors were in digits of different significance.

6. Predicted performance with random errors

The tests described above were all conducted with errors introduced periodically into a particular digit. In digital television recording and transmission systems, errors tend to be random and occur singly or in bursts. In such cases the performance of the error-protection system might well be limited by the occurrences of errors in sample words close together. Where the errors are introduced into each digit randomly, the performance of the system can be calculated on the basis that errors affecting digits of different significance of a particular sample are detected. However, errors cannot be corrected reliably if they occur in samples less than fourteen sample intervals apart.

At random error rates of 1 error in 10^5 bits, the probability of two errors occurring in the more significant digits of words closer than fourteen words apart is about 10^{-3}. This is about the same as the rate at which the error-protection system fails to correct errors in the two most significant digits on a critical picture like 'Formal Pond'. At a random error rate of 1 error in 10^4 bits the performance of the error-protection system would likely be entirely determined by the occurrences of errors in samples close together. However, it has been estimated that, at the output of the error-protection system the subjective effect of the uncorrected errors would be similar to that when an error rate of 1 in 10^6 exists and there is no error-protection.

7. Discussion

7.1. Limitations to the performance of the protection system due to quantisation effects

It was found that the error-protection system described here was not effective in reducing the effects of errors in the fourth digit or digits of lower significance. It was reported in Section 4.3 that some failures of the error-protection system to correct errors in the third significant digit, and most failures to correct errors in digits of lower significance, were not dependent on the frequencies present in the video signal. Although some failures at these points could be attributed to deficiencies in the practical measurement filter used, there were other effects that limited the performance of the error-protection system.

One effect, which was found to limit the ability of the error-protection system to correct errors in digits of lower significance, was traced to quantisation effects introduced into the signal at the video analogue-to-digital converter. Quantisation introduces wideband noise into the signal which is not subjected to the spectral limitations imposed on the signal by the low-pass filter which precedes the analogue-to-digital converter. Nor can this be removed by interposing a digital low-pass filter after the converter. These effects could only be reduced by transmitting more than eight bits for each digital video sample.

Estimates can be made of the effect of quantisation noise on the output signal from the measurement filter, assuming the quantisation errors in the original signal to be random. The r.m.s. value of the quantising error-signal at the output of the measurement filter can be taken as the r.m.s. value of the quantisation error of one sample multiplied by the root of the sum of the squares of the coefficients of the filter. This sum yields an r.m.s. value equal to $0{\cdot}79q$ (where q is the amplitude of one eight bit quantum step).

This spurious signal will not have any great effect on the accuracy of the corrections applied, but will limit the ability of the detection circuits to determine which samples are in error. For an error in the most significant digit, the output D of the measurement circuit for three consecutive sample positions will be $36q$, $\underline{0}$, $36q$ and the r.m.s. error in each value, approximately $\sqrt{2{\cdot}5} \times 0{\cdot}79q = 1{\cdot}25q$ (using again the root of the sum of the squares of the factors used to form D). For an error in the fourth significant digit, the outputs for D would be $2q$, 0, $2q$ with again an r.m.s. error of $1{\cdot}25q$ for each value. Assuming these quantising errors have a Gaussian probability distribution, there is a probability of about 0·2 that the noise will disturb the position of

the minimum in D such that an error in the fourth significant digit will not be corrected. There is also a high probability that additional minima might be produced in surrounding sample positions.

This situation could be improved by using a more sophisticated detector where the D signal is derived from more samples of the output signal from the measurement filter. A detector which uses six rather than two samples would be close to the optimum, and it would roughly halve the effects of the quantisation noise. With an improved detector, the performance of the error-protection system in correcting errors in the fourth significant digit might be limited by unwanted in-band responses of the measurement filter rather than the quantisation of the signal.

7.2. Performance compared with that of an error-protection scheme based on Wyner-Ash error correction

A system of error-protection of the digital video signal based on Wyner-Ash error correction has been developed[2] and its performance assessed.[3] In this system, the four most significant digits of a digital television signal are equally protected using a system of check digits. Transmission of these check digits increases the bit-rate of the signal for transmission by 14%. The efficiency of this error-protection system is summarised in Fig. 13 reproduced from Reference 2. This gives the error rate at the output of the system as a function of the rate at which random errors are introduced into the signal during transmission. It applies to the four most significant digits.

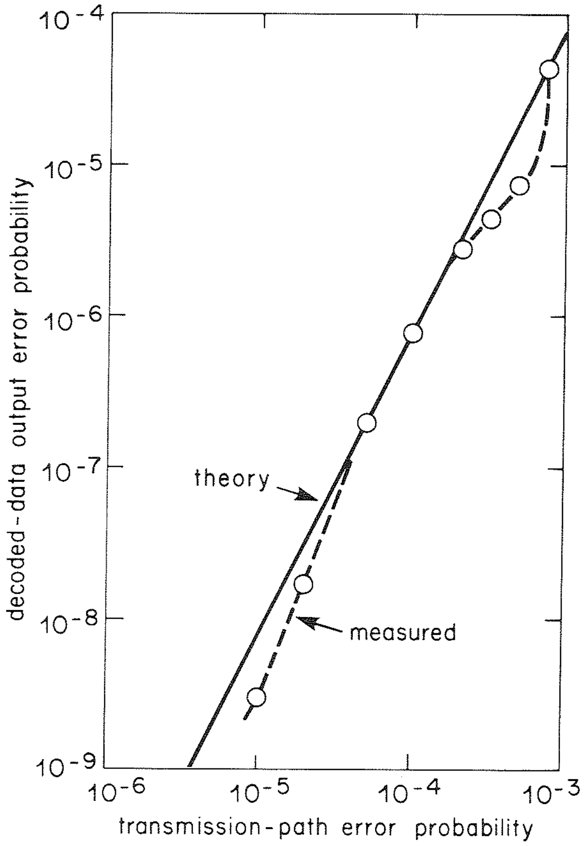


Fig. 13 - Performance of the experimental Wyner-Ash error corrector

The equivalent figures for the error-protection system based on waveform estimates, give a similar reduction in errors for an error rate of 10^{-5} and will follow a similar law. However, with this system, errors in the third significant digit are not so well protected and there is no effective protection of the fourth significant digit.

Overall, it would not be expected that the performance of the error-protection system based on waveform estimates would be as good as that for the Wyner-Ash system. However, with an improved measurement filter characteristic and improved measurement circuits, the performance of the two systems might be similar.

7.3. Instrumental complexity

The main component in the instrumentation of this error-protection scheme is the adjustable measurement filter. The one used in the tests comprised twelve boards each of 48 integrated circuits. Were a final error-protection system to be instrumented, a much simpler filter could be constructed where the coefficients would not be adjustable, thereby reducing the complexity of this part of the system. However, bearing in mind that it would be desirable to improve the accuracy of the coefficients and thus reduce the unwanted signal responses at lower frequencies, it is likely that the number of integrated circuits would be about 150.

The measurement circuits used in the tests were relatively simple but required about 120 integrated circuits. If more samples were to be used to locate the samples in error, this number might be increased.

Overall, it is estimated that a practical error-protection system based on these principles would require one terminal to process the signal before decoding, comprising some 300 integrated circuits.

8. Conclusions

The error-protection system described in this Report could, with certain improvements, be used to give effective error-protection for p.c.m. television signals where the word-rate is $3f_{sc}$ or higher. The system offers an advantage over more conventional error-protection systems, in that it does not rely on the use of parity digits and therefore the digit rate is not increased for transmission or recording. A disadvantage of this system is that it is more complex and requires more costly instrumentation.

Tests, using errors generated at a regular rate in digits of one particular significance at a time, showed that the error-protection system which was instrumented gave a good degree of protection against errors in the three most significant digits. The performance depended on the test picture coded and for a critical picture, errors in the most significant digit were reduced by a factor of 10^3. The factor was 500 for the second significant bit and 50 for the

third bit. With less critical pictures the errors were further reduced. To some extent, the reduced efficiency for protection of digits of lower significance is consistent with the reduced visibility of errors in these bits. However, it has been found in tests with other systems that some protection of the fourth significant digit is beneficial.

It has been calculated that the degree of protection against random errors would be much the same as for periodic errors as long as the random error rate is less than 1 error in 10^5 bits. At higher random-error rates the degree of protection would be reduced.

One major limitation to the performance of the error-protection system arose through eight-bit quantising noise, present in the p.c.m. video signal, preventing the measurement circuits from correctly identifying which samples were in error. With more complex measurement circuits, this effect could be reduced and some protection obtained against errors in the fourth significant digit.

The performance of the error-protection system would have been further improved had coefficients of the digital transversal measurement filter not been so coarsely quantised. For the filter used in the tests there were only 128 values available for the coefficients in the range −1 to +1. Measurement filters giving a higher degree of rejection of in-band frequency components of picture signals could have been simulated had there been a finer control on these coefficients.

With improvements in the measurement circuits and the measurement filter, it is predicted that the error-protection obtained with this system might be similar to that obtained with a more conventional error-protection system based on Wyner-Ash error correction and using parity digits which increase the transmitted or recorded bit-rate by 14%.

The system based on waveform estimates might find application where the digital television sample rate is $3f_{sc}$ or higher and it is not possible to incorporate extra check digits in the digital television signal prior to transmission or recording.

9. References

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